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Soukhanovskii

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Contribution to Plasma Physics

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Multi-fluid code simulations including anomalous non-diffusive transport of plasma and impurities in the tokamak SOL

A. Yu. Pigarov^{*1,2}, S. I. Krasheninnikov^{1,2}, T. D. Rognlien³, W. P. West⁴, B. LaBombard⁵, B. Lipschultz⁵, R. Maingi⁶, and V. Soukhanovskii⁷

¹ MAE Center for Energy Research, University of California at San Diego, EB-Unit-II, 9500 Gilman Dr., Mail Stop 0417, La Jolla, CA 92093-0417, USA

² also at National Research Center “Kurchatov Institute”, Moscow, Russia

³ Lawrence Livermore National Laboratory, Livermore, CA, USA

⁴ General Atomics, San Diego, CA, USA

⁵ Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA, USA

⁶ Oak Ridge National Laboratory, Oak Ridge, TN, USA

⁷ Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ, USA

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Fast intermittent transport has been observed in the scrape-off layer (SOL) of major tokamaks including Alcator C-Mod, DIII-D, and NSTX. This kind of transport is not diffusive but rather convective. It strongly increases plasma flux to the chamber walls and enhances the recycling of neutral particles in the main chamber. We discuss anomalous cross-field convection (ACFC) model for impurity and main plasma ions and its relation to intermittent transport events, *i.e.* plasma density blobs and holes in the SOL. Along with plasma diffusivity coefficients, our transport model introduces time-independent anomalous cross-field convective velocity. In the discharge modelling, diffusivity coefficients and ACFC velocity profiles are adjusted to match a set of representative experimental data. We use this model in the edge plasma physics code UEDGE to simulate the multi-fluid two-dimensional transport for these three tokamaks. We present simulation results suggesting the dominance of anomalous convection in the far SOL transport. These results are consistent with the hypothesis that the chamber wall is an important source of impurities and that different impurity charge states have different directions of anomalous convective velocity.

1 Introduction

Fast intermittent cross-field plasma transport has been observed in the edge and scrape-off layer (SOL) of many tokamaks including Alcator C-Mod, DIII-D, and NSTX (see, respectively, the references [1], [2], and [3]) for details). The coherent plasma structures, called blobs [4], have been found to rapidly propagate (even ballistically) toward the wall. This kind of transport is convective rather than diffusive. It is characterized by strongly increased plasma fluxes to chamber walls and by enhanced recycling of neutrals in the main chamber [1, 5]. The non-diffusive transport may significantly alter not only the particle recycling but also the degree of divertor detachment, plasma radiation loss, impurity sources and transport, peak power loads, and plasma-wall interactions.

The effects of non-diffusive intermittent transport on the macroscopic plasma transport and particle recycling occurring in the tokamak edge have been studied in Refs. [5, 6] with 2D fluid code UEDGE [8]. Along with anomalous plasma diffusivity coefficients (D_{\perp} , χ_{\perp}), our transport model introduces a time-independent anomalous cross-field convective (ACFC) velocity V_{conv} [5]. For the main plasma ion specie, V_{conv} is directed outwards. In discharge modeling, 2D profiles of plasma diffusivity coefficients and V_{conv} are adjusted to match representative set of experimental data. Inclusion of V_{conv} allowed us to reproduce properly not only individual properties of selected low (L) and high (H) confinement mode shots, but also important experimental features

* Corresponding author: e-mail: apigarov@ferp.ucsd.edu, Phone: +1 858 822 4916, Fax: +1 858 534 7716

of a special series of shots focused on edge plasma study, *e.g.* the so-called Simple-As-Possible-Plasma (SAPP) series using the lowest input power L-mode shots on DIII-D [6, 7]. Our results [6] showed the dominance of ACFC in the far SOL transport and the transition to main chamber recycling fueling (MCRF) regime with an increase in the discharge density $\langle n_e \rangle$. An important role of ACFC in plasma transport for H-mode shots was discussed in [5, 6].

The detailed description of impurity transport and sources is one of the most challenging issues in the edge plasma physics. Recent experiments carried out on C-Mod (see Ref. [10]) and DIII-D (see Ref. [11]) tokamaks indicated that the main chamber walls could be an important source of impurities. These observations are consistent with fast non-diffusive transport in the SOL. Moreover, recent experiments on non-diffusive transport in DIII-D edge [12] and theoretical models [9, 13] have shown two kinds of intermittent objects: plasma density "blobs" and "holes". The blob objects, which contain a hot and dense plasma, propagate radially toward the chamber wall. In contrast, the hole objects, which carry smaller (near-wall) plasma density, propagate inward. It is expected [9] that these holes play important role in the non-diffusive transport of low impurity charge states by enhancing the radial transport of these ions. The effect of holes on impurity transport should be carefully investigated and incorporated into the edge codes.

As the next step in our studies, we discuss the ACFC model for impurity and main plasma ions. We apply the multi-fluid code analysis on medium size tokamaks: DIII-D, C-Mod, and NSTX. The results of the present paper show that edge plasma in all these tokamaks can be simulated under the same assumptions of anomalous multi-fluid cross-field transport.

2 Model for 2D profile of anomalous cross-field convective velocity

In our cross-field transport model, the convective term plays very important specific role. This term provides transport of plasma ions with the velocity $V_{conv}(\psi_n, \theta)$ in a given direction. For the majority ion species, this anomalous convective flux is due to averaging over blobs causing infrequent, but large, transport events directed outward. The typical profile of plasma V_{conv} is shown in Fig.1. The V_{conv} strongly increases with minor radius. The radial gradient of V_{conv} is given in the normalized poloidal magnetic flux space ψ_n . On a given magnetic flux surface, V_{conv} has maximum at the outer mid-plane. The poloidal (θ -coordinate) profile is updated with respect to the profile used previously in [5]. An important finding of recent UEDGE simulations is that significant anomalous convection should occur on the inboard part of the torus. One possible reason is that the blob movement outward on the outboard side is a cause of strong MHD perturbation to the magnetic flux tube that may result in this tube moving toward the wall on the inboard side. The inboard/outboard asymmetry is typically 1 : 3. In the divertor and private flux regions, V_{conv} is taken about 1/3 of its mid-plane value. Typically, these values of V_{conv} in the divertor are used to match a set of diagnostics in this region, for example, the Langmuir probe, IR TV, and Thomson laser scattering (TLS) on DIII-D.

The $V_{conv}(\psi_n, \theta, z)$ profile for impurity ions is the focus of our present studies. In our UEDGE code model, each impurity ion charge state is assigned its own convective velocity:

$$V_{conv}(\psi_n, \theta, z) = V_{conv}^{BP}(\psi_n, \theta) * \Phi_z(z), \quad (1)$$

where V_{conv}^{BP} is the ACFC velocity of background plasma (*i.e.* of D^+ ions), $\Phi_z(z)$ is the distribution function (DF), and z denotes the charge state of the impurity ion, $z \geq 1$. The $\Phi_z(z)$ distribution suggests that the lowest impurity charges states are either partially or completely entrained in plasma density holes, so that their V_{conv} is either strongly reduced in comparison with background plasma convective velocity or completely directed toward the core plasma, respectively. At the same time, the highest impurity charge states behave more like the main plasma ions, *i.e.* these states are entrained into blobs predominantly moving toward the wall. Hereafter, $V_{conv}(D^+)$ and $V_{conv}(C^{+z})$ denote the local values of ACFC velocity for D^+ and C^{+z} ions, respectively. For the DF $\Phi_z(z)$ of carbon ions, we use the $\Phi_{CCC}(z)$ distributions which have $V_{conv}(C^{+z}) < V_{conv}(C^{+(z-1)})$, $V_{conv}(C^{+6}) = V_{conv}(D^+)$, and $-1 \leq V_{conv}(C^{+z})/V_{conv}(D^+) \leq 1$ and which are characterized by a single parameter $\eta_{ccc} = [V_{conv}(C^{+1}) + V_{conv}(C^{+2}) + V_{conv}(C^{+3})]/V_{conv}(D^+)$. This parameter continuously decreases from +3 (when all V_{conv} are the same as for D^+) down to -3 (for the case when C^{+1} , C^{+2} , C^{+3} ions are convected in direction opposite to the D^+ ion direction but at the same speed). In this work, we test different distribution functions $\Phi_{CCC}(z)$ over charge states (some of these DF are shown in Fig.2) searching for those distributions that give better fits to available experimental data.

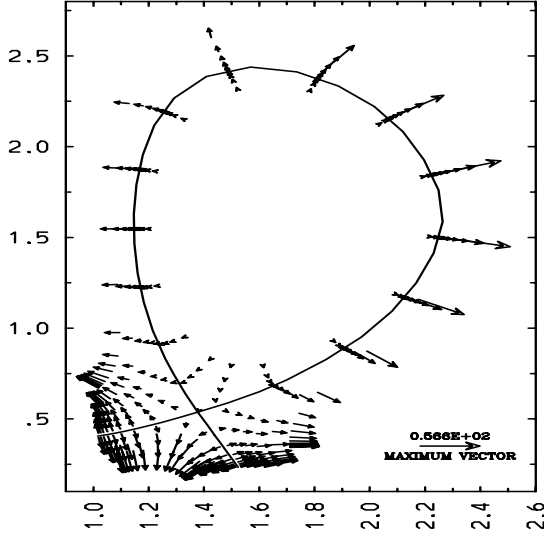


Fig. 1 Vector plot of anomalous convective cross-field velocity V_{conv} for majority ion species (D^+) related to DIII-D L-mode shot 105500.

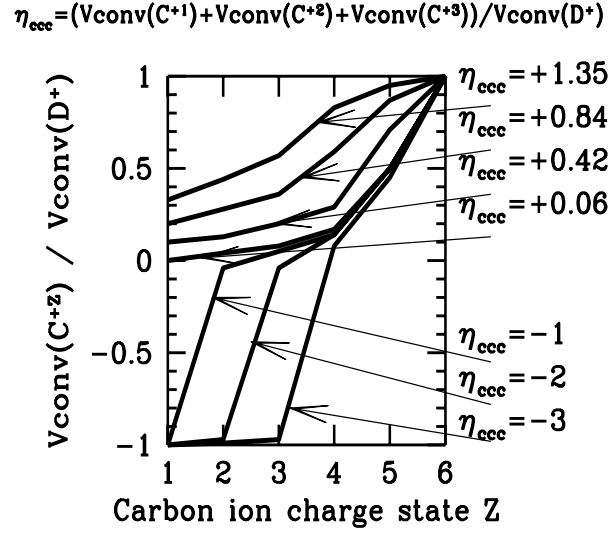


Fig. 2 Model distributions of anomalous convective velocity V_{conv} for carbon ion charge states C^{+z} . This family of distributions is characterized by parameter η_{ccc} .

3 Results of impurity transport modeling with UEDGE

With the UEDGE code, we simulate multi-fluid transport in a series of L-mode discharges obtained on DIII-D, NSTX, and C-Mod. In DIII-D and NSTX cases, we model carbon impurities (atoms and six charge states), while for C-Mod, we use boron impurities. We use realistic impurity sources due to physical sputtering, chemical sputtering, and self-sputtering (the sputtering coefficients are similar to those incorporated into the DIVIMP code [14]). We assume D_{\perp} and χ_{\perp} to be constants outside the separatrix. In the core plasma region, these coefficients are taken to decrease slightly (and strongly, for NSTX) in the radial direction (ψ_n -space) for a better match to the in/out SOL profile asymmetry.

At present, a simple diffusive model is used in UEDGE to describe the transport of impurity neutrals. The characteristic scale length in diffusive model is $\lambda_{C0} = \{2T_{C0}/[M_C\nu_i(\nu_i + \nu_{cx} + \nu_{el})]\}^{1/2}$, where ν_i , ν_{cx} , ν_{el} are the frequencies for ionization, charge exchange, and elastic scattering of an atom, M_C is the mass of carbon atom. It is assumed that effective neutral gas temperature is $T_{C0} = \zeta_{th}T_i + (1 - \zeta_{th})T_{spt}$, where parameter $0 \leq \zeta_{th} \leq 1$ determines the fraction of thermalized atoms, $T_{spt} \approx 1$ eV is the characteristic temperature of primary sputtered particles. This is crude approximation, which introduces an additional uncertainty related to impurity atom penetration. Typically, ionization of carbon atoms is the dominant process in the SOL, so we take $\zeta_{th} = 0.01$ in most of our calculations.

Here we consider an interesting case related to the lowest density SAPP-series shot 105500 on DIII-D. Amongst the SAPP shots, this shot has the highest concentration of C^{+6} impurity measured in the core plasma, whereas the particle flux to chamber walls is the lowest. Shot 105500 has been already modelled with UEDGE in Ref. [6] based on fixed impurity fraction model. This time, we perform a more detailed, multi-fluid analysis of the shot. We focus on the study of the effect of anomalous convection of impurities on edge plasma parameters. The detailed comparison between experimental and UEDGE data for the hydrogen and carbon ion spectroscopy for this shot is given in [15] (including the realistic 3D model of visible light reflection from the chamber wall).

In our analysis we use the following three basic parameters: (i) the peak temperature at the outer divertor plate (T_{ed}), (ii) the relative concentration $\eta_{C6} = [C^{+6}]/n_e$ of C^{+6} ions at the mid-plane on the $\psi_n = 0.95$ magnetic flux surface, and (iii) the mid-plane horizontal view chord brightness $B_{mid}(CIII)$ of CIII-ion line at 4650 Å. These three parameters are calculated by UEDGE and routinely measured on DIII-D, respectively, with Langmuir probes and divertor TLS system, with neutral-beam charge exchange recombination spectroscopy (NB CERS) in combination with TLS system for the SOL profiles of plasma density and temperature, and with fast filterscopes. The concentration of fully ionized carbon (C^{+6}), η_{C6} , depends strongly on both edge transport and sputtering

sources. The $B_{mid}(CIII)$ brightness may characterize the carbon ion sources in the main chamber, whereas T_{ed} is indicative of plasma state in the divertor.

First of all, we answer the following question: can anomalous cross-field transport of impurity ions be purely diffusive in the case when background plasma transport is dominated by the radial intermittent convection? We perform two series of UEDGE runs and present our results in Fig.3. In the first series (curves with filled hexagons), we increase the diffusion coefficient $D_{\perp}(z)$ for all impurity ions by the same factor with respect to $D_{\perp}(D^+)$ of background plasma. As seen, the simple increase in impurity species diffusion only increases the inconsistency between calculated and experimental data. For instance, an increase in D_{\perp} results in η_{C6} decreasing since the leakage of C^{+6} and C^{+5} ions from the core region increases more strongly than the fluxes of lower charge state ions into the core. In the second series (curves with open circles), we assume the following distribution function for local impurity diffusion coefficient: $D_{\perp}(C^+) = D_{\perp}(D^+) \gamma_{CI}$ for C^+ -ion and $D_{\perp}(z) = D_{\perp}(D^+) [1 + (\gamma_{CI} - 1)/z^2]$ for other C^{+z} carbon ions, where parameter $\gamma_{CI} \geq 1$. In this series, experimental levels of T_{ed} and η_{C6} can be reached only at very high values of $D_{\perp}(C^+)/D_{\perp}(D^+)$ but calculated B_{mid} is higher than that measured. Moreover, the fact that the required values of $D_{\perp}(C^+)$ here exceed the Bohm value by more than a factor of 10 is indicative of non-diffusive transport of impurities in the SOL. So, purely diffusive models are unsuitable for description of impurity transport when anomalous convection dominates in the SOL plasma transport.

Next, we run UEDGE with different ACFC velocity distribution functions $\Phi_{CCC}(z)$ over charge states z of carbon impurity ion (Fig.2). For each test distribution we adjust V_{conv}^{BP} , D_{\perp} , χ_{\perp} , and wall albedo to match the radial SOL plasma density and temperature profiles, core particle balance, D_{α} signals measured by horizontal and tangential filterscopes at mid-plane, and mid-plane gas pressure. The diffusivity coefficients, D_{\perp} and $\chi_{i\perp}$, are taken to be the same for all ion species. In doing so, we found (as in Refs. [5, 6]) that anomalous plasma convection is the dominant plasma transport process in the SOL.

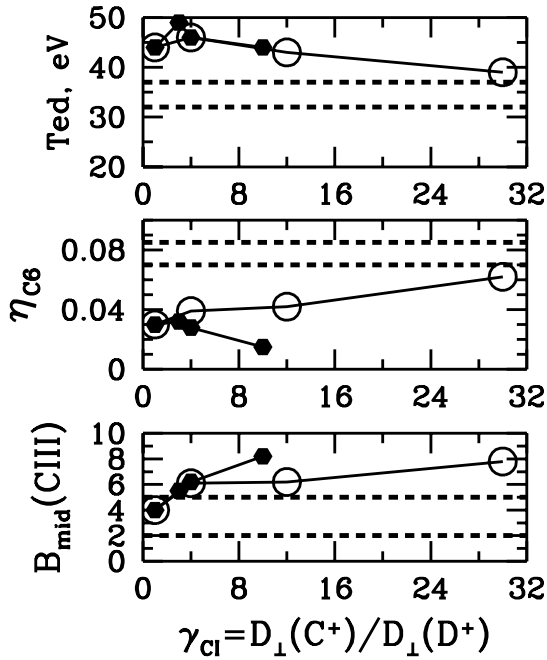


Fig. 3 Variation of T_{ed} , η_{C6} , and $B_{mid}(CIII)$ with the ratio γ_{CI} of cross-field diffusion coefficients of carbon and deuterium ions ($D_{\perp}(C^+)$ and $D_{\perp}(D^+)$). On each panel, experimental DIII-D data are scattered between two horizontal broken lines.

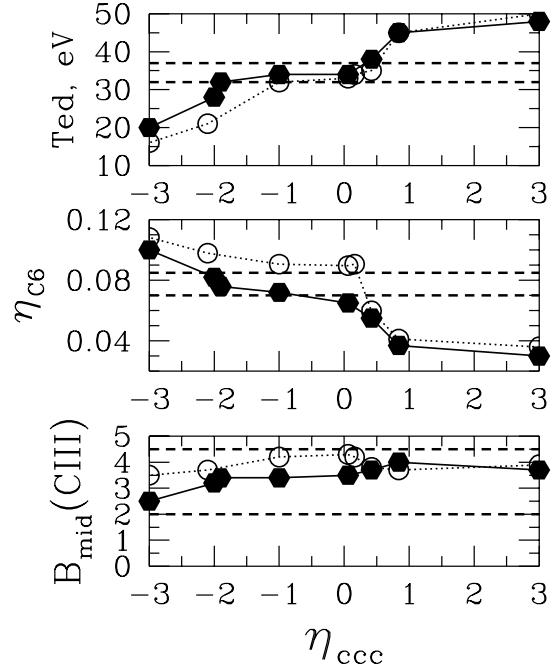


Fig. 4 Variation of T_{ed} , η_{C6} , and $B_{mid}(CIII)$ with impurity model parameter η_{ccc} calculated for DIII-D shot 105500 by using $\zeta_{th} = 0.01$ (solid curves) and $\zeta_{th} = 1$ (dotted curves). On each panel, experimental DIII-D data are scattered between two horizontal broken lines.

The results of UEDGE simulations including anomalous impurity ion convection are given in Figs. 4,5 for the DIII-D shot under consideration. In Fig.4, we compare the results obtained for low ($\zeta_{th} = 0.01$, solid lines

with hexagons) and high ($\zeta_{th} = 1$, dotted lines with circles) penetration of carbon atoms. In both cases, T_{ed} and η_{C6} are strong functions of η_{ccc} . The weaker the transport of atoms through the SOL, the stronger should be the inward cross-field convective transport of few lowest charge states of carbon ion in order to match the measured level of core plasma contamination η_{C6} . As seen, if $\eta_{ccc} \geq 0.5$, i.e. V_{conv} for all impurity ions is directed toward the wall, most of the experimental data is not matched with UEDGE. In the realistic case when ζ_{th} is small, experimental values are well matched with UEDGE in a wide range $-2.5 \leq \eta_{ccc} \leq -1$ when C^+ and C^{++} ions are rapidly convected inward. The chemical sputtering (CS) yield is very uncertain at surface temperatures close to room temperature and low energies of incident particles that is typical for L-mode. The effect of CS yield uncertainty is studied in Fig.5. We display UEDGE results without (curves with open circles) and with (curves with filled hexagons) chemical sputtering of the wall at $T_w = 300K$ for $\zeta_{th} = 0.01$. As seen, the smaller the sputtering source, the more actively the lowest charge states should be convected inward in order to match experimental data.

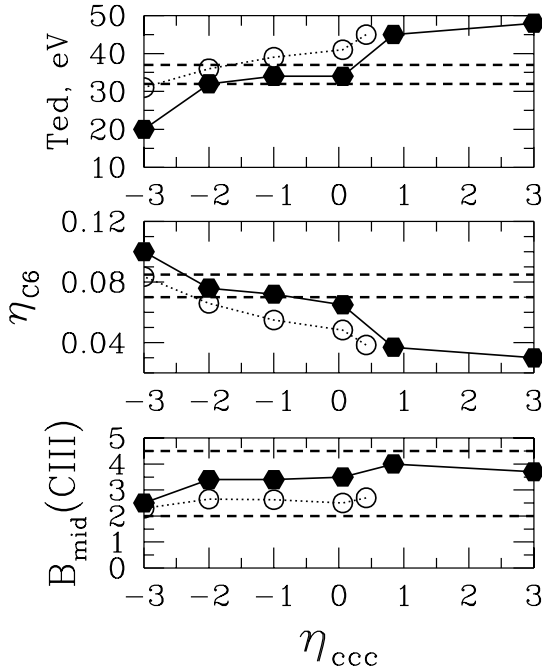


Fig. 5 Variation of T_{ed} , η_{C6} , and $B_{mid}(CIII)$ with impurity model parameter η_{ccc} calculated for DIII-D shot 105500 with (solid curves) and without (dotted curves) chemical sputtering of the chamber wall.

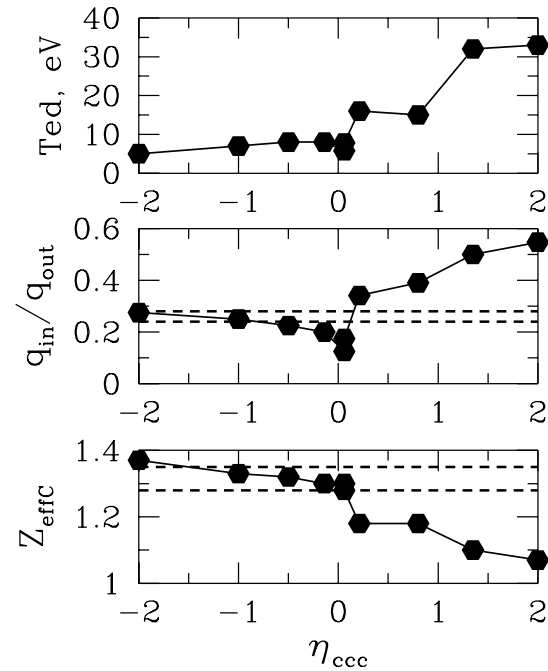


Fig. 6 Variation of Z_{effC} , inner plate peak T_{ed} , and q_{in}/q_{out} -ratio for NSTX shot 109033. Experimental NSTX data are scattered between two horizontal broken lines.

Important results were also obtained in the multi-fluid modelling of edge plasma for NSTX spherical tokamak. We simulate the low-power L-mode shot 109033 at 253 ms. This is the NSTX shot in which the discharge density $\langle n_e \rangle \approx 2.4 \times 10^{19} m^{-3}$ is close to the density of DIII-D shot 105500 considered above. With the UEDGE code, we iteratively match the following: (i) particle flux balance at the core interface consistent with the NBI fueling rate and with the rate of core plasma density increase, (ii) radial profiles of n_e and T_e measured at mid-plane by TLS on both the inboard and outboard parts of the torus, (iii) T_i profile measured by CERS, and (iv) neutral gas pressure measured at outboard mid-plane location. In addition, UEDGE data obtained for different η_{ccc} are compared in Fig.6 to the experimental data, namely, the carbon ion Z_{effC} measured by CERS in the outboard core region around $\psi_n = 0.7$ and the ratio q_{in}/q_{out} measured by IR TV, where q_{in} and q_{out} are the peak heat fluxes on the inner and outer divertor plates. As seen on Fig.6 the experimental and simulated data are in good agreement for $\eta_{ccc} < -0.5$, i.e. in the case when non-diffusive impurity transport is strong and the lowest states may be actively convected inward.

The dominant plasma impurity species in recent Alcator C-Mod experiments is boron [11]. In UEDGE modelling, the ACFC velocity profile, $V_{conv}(\psi_n, \theta, z)$, for boron ions is given by Eq.1. For the distribution function

$\Phi_z(z)$ over charge state of boron ions, $1 \leq z \leq 5$, we use the $\Phi_{BBB}(z)$ distributions which have $V_{conv}(B^{+z}) < V_{conv}(B^{+(z-1)})$, $V_{conv}(B^{+5}) = V_{conv}(D^+)$, and $-1 \leq V_{conv}(B^{+z})/V_{conv}(D^+) \leq 1$ and which are characterized by a single parameter $\eta_{BBB} = [V_{conv}(B^{+1}) + V_{conv}(B^{+2}) + V_{conv}(B^{+3})]/V_{conv}(D^+)$. A family of $\Phi_{BBB}(z)$ distribution functions is shown on Fig.7.

We perform the UEDGE code simulation of impurity transport based on anomalous cross-field convection model for the C-Mod Ohmic heating shot numbered 1030630019. The resulting UEDGE solutions for this shot match the following: (i) particle flux balance at the core plasma interface, (ii) outer SOL profiles of n_e and T_e measured by TLS and reciprocating probes; (iii) gas pressure in the main chamber at the mid-plane, (iv) D_α brightness of selected view sights measured by CCD cameras, and (v) Z_{eff} . Impurity concentration level in the core plasma is characterized by the effective plasma charge Z_{eff} , the radial profile of which is measured on C-Mod. The variation of calculated Z_{eff} with parameter η_{BBB} in impurity transport model is shown on Fig.8. As seen, the negative values $\eta_{BBB} < -1$ are consistent with the measured level of Z_{eff} in the core plasma, so that non-diffusive impurity transport may play an important role in core plasma contamination in C-Mod.

$$\eta_{BBB} = (V_{conv}(B^{+1}) + V_{conv}(B^{+2}) + V_{conv}(B^{+3})) / V_{conv}(D^+)$$

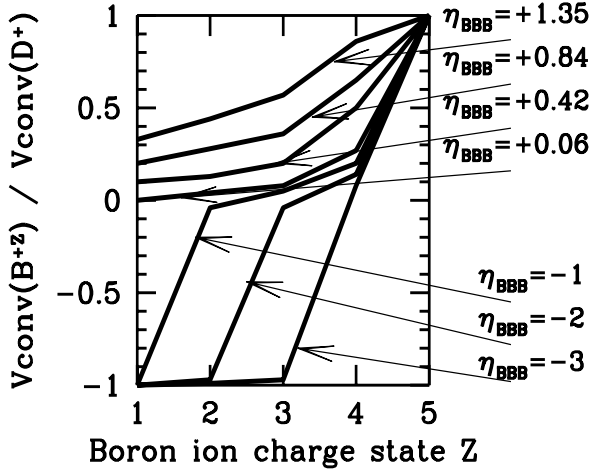


Fig. 7 Model distributions of anomalous convective velocity for boron ion charge states B^{+z} for a set of η_{BBB} values.

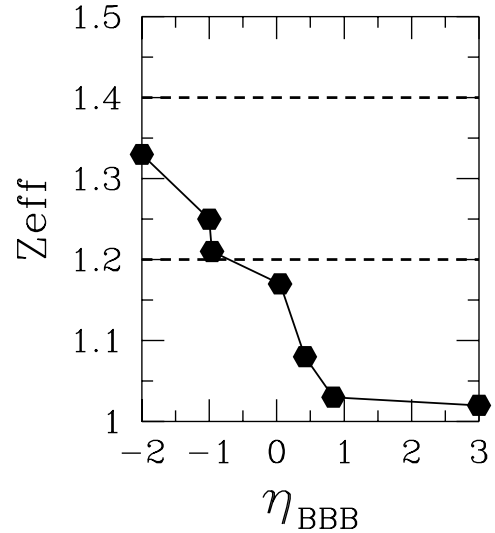


Fig. 8 Variation of Z_{eff} with impurity model parameter η_{BBB} for C-Mod shot 1030630019.

Our recent results of UEDGE modelling for DIII-D, NSTX, and C-Mod suggest that in L-mode shots the chamber wall is important source of impurities and that this source can cause significant contamination of the core plasma. In the case of DIII-D shot, an important role of wall sputtering source can be understood by inspecting Fig.5. The calculated B_{mid} has a relatively weak dependence on η_{ccc} since impurity sputtering source is practically not changed while $\eta_{ccc} \geq -2$. Moreover, as follows from the UEDGE calculation with accounting for wall chemical sputtering (WCS), the WCS is 40-50% of the total sputtering source of wall. As seen, elimination of WCS from the UEDGE modelling results in a reduction in the core impurity concentration η_{C6} by approximately the same 40% for these plasma conditions.

4 Some results on cross-field transport comparison in medium size tokamaks

Using multi-fluid UEDGE to evolve impurities, we have re-done simulations for L-mode SAPP series on DIII-D and confirmed our previous results and major conclusions [6] obtained with a fixed impurity fraction model. In recent modeling we took more uniform poloidal distribution of $V_{conv}(\theta)$ including the inboard region that allowed us to match the data measured by tangentially as well as horizontally viewing mid-plane filterscopes (see [15]). Solutions were obtained using the same values of $D_\perp = D_\parallel^* = 0.15 \text{ m}^2/\text{s}$ and $\chi_\perp = \chi_\parallel^* = 0.8 \text{ m}^2/\text{s}$ for all SAPP shots in a wide range of discharge densities $\langle n_e \rangle$ at the same power input. In addition, we simulated selected L-mode shots of NSTX and C-Mod. Special experimental features (inboard gas puff and inboard/outboard profile asymmetry on NSTX or vertical divertor plates on C-Mod) were modeled.

We use the simulated SAPP DIII-D data as a baseline for cross-machine comparison. We find that fitted diffusivity coefficients on NSTX and C-Mod tokamaks correspond to the D_{\perp}^* and χ_{\perp}^* (obtained for DIII-D) being scaled similar to Bohm, $\propto T_e^s/B_t^s$, where T_e^s and B_t^s are the electron temperature and the toroidal magnetic field at the outer mid-plane on the plasma core boundary surface. The convective velocity at the wall, $V_{conv}(w)$, is deduced by matching experimental data on main-chamber recycling, in particular, the mid-plane D_{α} brightness and gas pressure that are $\propto \langle n_e \rangle^3$ for a series of shots (see [6, 9]), yielding a density dependence with $V_{conv}(w) \propto \langle n_e \rangle^{\beta}$, $1 \leq \beta \leq 2$. A nearly linear increase of $V_{conv}(w)$ with $\langle n_e \rangle$ is predicted by UEDGE for the SAPP series (DIII-D) and 100517 series (C-Mod) of L-mode shots. Since blobby transport is related to $\vec{E} \times \vec{B}$ drift from polarization, V_{conv} should decrease inversely with B_t . For discharges with similar plasma density $\langle n_e \rangle \approx 2.4 \times 10^{19} \text{ m}^{-3}$, we obtain $V_{conv}(s) \approx 40 \text{ m/s}$ at the separatrix of low- B_t tokamak ($B_t \approx 0.4 \text{ T}$, NSTX shot 109033) vs. $V_{conv}(s) \approx 10 \text{ m/s}$ ($B_t \approx 1.9 \text{ T}$, DIII-D shot 105500). For C-Mod ($B_t \approx 5.6 \text{ T}$, $\langle n_e \rangle \approx 10^{20} \text{ m}^{-3}$, shot 100517017), we obtained $V_{conv}(s) \approx 10 \text{ m/s}$, i.e., V_{conv} may scale as a combination of $\langle n_e \rangle$ and B_t . For shots considered, the best agreement between simulated and experimental data gives the impurity convection parameter as $-2 \leq \eta_{ccc} \leq -0.5$. A detailed comparison of cross-field transport in tokamaks will be reported elsewhere.

5 Conclusions

We have used the multi-fluid transport code UEDGE to perform extensive simulations for L-mode edge plasmas in medium size tokamaks including C-Mod, DIII-D, and NSTX. Our previous and recent results show that fast non-diffusive intermittent plasma transport (which is modeled by UEDGE as anomalous cross-field convection) can be the dominant SOL transport mechanism in all these tokamaks. By matching the main chamber recycling data in tokamaks, we find that anomalous convective velocity in the far SOL should increase with discharge density $\langle n_e \rangle$. Moreover, cross-tokamak comparison shows that anomalous convective velocity should increase with decrease in toroidal field strength in agreement with theoretical models and measurements of edge turbulence indicating that non-diffusive transport is related to $\vec{E} \times \vec{B}$ drift from polarization.

In our modeling of different tokamaks, the best agreement between the calculated and experimental data gives the impurity cross-field transport model in which anomalous cross-field convection dominates in the SOL transport, the background plasma ions and high charge state impurity ions are convected toward the wall, while the low charge state impurity ions either are convected toward the core plasma or, at least, their convection outward together with majority ion species is significantly reduced. Our analysis also shows that impurities from wall can cause significant contamination of core plasma if impurity transport in the SOL is fast and non-diffusive. Therefore, for further validation of impurity model, we intend to expand our analysis on matching the multi-fluid code results with an extensive set of DIII-D experimental spectroscopic data for each impurity ion charge state and more detailed data from impurity transport experiments on other tokamaks.

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